

An Antenna Array for Radar Astronomy Studies in the 20 to 55 Mc Range

by

H.T. Howard

Contract AF19(604)-7436

Air Force Cambridge Research Laboratories, OAR, USAF

Bedford, Massachusetts

Project No. 5629, Task No. 562901

Technical Report No. 3

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United States Air Force

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RADIOSCIENCE LABORATORY

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AN ANTENNA ARRAY FOR RADAR ASTRONOMY STUDIES IN THE
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SUMMARY

10686 *short*

The discipline of radar astronomy requires antennas capable of handling large peak and average powers over a wide frequency range, while providing both high directive gain and enough steerability to illuminate targets for extended periods of time.

This report discusses the design and construction of a branch-fed, variable-phase, 20-60 mc array of 48 log-periodic elements. Phasing to control beam direction is described and the correction necessary for ionospheric refraction is presented in terms of vertical incidence critical frequency. The array gain as measured by moon bounce techniques is found to be in good agreement with the theoretical value. *pulling*

INTRODUCTION

An antenna array has been constructed at Stanford University for radar studies of the moon, cislunar gas, and solar corona. The array is designed to handle 500 kilowatts of CW power in the 20 to 55 mc range. It is currently being used with either a 300-kw or 50-kw average-power transmitter, or with both simultaneously. These transmitters are linear amplifiers and will produce 600 kilowatts and 100 kilowatts peak envelope power, respectively.

The lower VHF and upper HF portion of the spectrum was chosen for the array to make possible radar studies of soft targets such as the solar corona and the interplanetary medium. For example, we are interested in studying the propagating medium between the earth and moon by measuring the effects of the medium on moon-reflected signals. These effects vary as λ or λ^2 , and for this reason the lowest possible frequency that can escape from the earth's ionosphere is desirable. The array gain combined with high transmitter power make possible moon reflections with sufficient strength to perform precise doppler and polarization measurements.

The returned signal's doppler shift is a function of both range rate and the radar wave's phase velocity over the path. By performing the

measurement on 25 and 50 mc simultaneously, it is possible to cancel range rate and leave only that part due to change in phase velocity. This contribution is typically a few tenths of a cycle per second and is a measure of the change of electron content over the entire earth-moon path. At the same time total polarization rotation of the signal is measured and, from this, total ionospheric electron content can be derived. It is possible to separate the ionospheric change from that occurring in the rest of the path because the signal's polarization is determined by a combination of the earth's magnetic field and ionization, while the doppler measurement is sensitive to ionization change only. Results of these investigations have been published elsewhere. [Refs. 1, 2]

EQUIPMENT

The various areas within the disciplines of radio and radar astronomy place different requirements upon antennas. Many of these requirements are obvious, such as the high angular resolution attainable with interferometers and the high-gain, narrow-beamwidth obtained with large dishes at short wavelengths. In the present case, however, there are several other factors to consider.

The radar produces its information principally in the form of time delay, polarization, doppler spread, and signal strength, with angular resolution usually being of less importance. High gain is desirable from the signal-to-noise ratio standpoint, but the possibility of several degrees of refraction in the earth's ionosphere makes the narrowest usable beamwidth fall between about 0.5 and 3 degrees. A dish would have to be 1000 feet in diameter to produce a three degree beamwidth at 25 mc and, even for these low frequencies, a fully steerable one would be quite expensive. There are a number of cheaper alternatives including dishes and cylinders of limited steerability but the most economical arrangement is that of a fixed array with beam movement accomplished by variable phasing. Experience with both types of antennas in the past has shown that the cost for a fully steerable aperture can be five to ten times as great as that for an equivalent fixed array. By selecting array orientation and shape properly, it is possible to produce a fan beam, narrow in declination and wide in right ascension, to provide data several hours per day.

Since it was desired to have flexibility to work with other experimenters who have large antennas on several different frequencies, it was decided to build a frequency-independent array to cover the transmitter's full design range of 20 to 55 mc. An initial theoretical and model study performed by Granger Associates of Palo Alto, California, indicated that transposed dipole log periodic antennas with the apex angles (α & ψ) = 60° and the design factor (τ) = 0.9 would be suitable as individual array elements. This configuration, shown in Fig. 1, produces equal E and H plane beamwidths of about 60 degrees. Two-inch open-wire line runs from the apex back to the cross boom and down the support pole. The small, structural cross piece near the nose is a micarta block. The 36-foot main booms and cross booms are 4-inch aluminum (6061-T6) tube and the individual elements are 1-inch aluminum tube. An assembled antenna weighs 225 lbs and has been designed to withstand 70 mph winds. Feed point impedance is 470 ohms with less than 2/1 VSWR over most of the design range. Individual elements such as this have been successfully used to feed the Stanford Research Institute's 150-foot dish at powers to 50 kw with no breakdown.

Forty-eight of these elements are used in the array. The final configuration, shown in Fig. 2, consists of two rows of 24 antennas each, with 50-foot separation between antennas and 65 feet between rows. These separations represent a compromise between main lobe shape and the need for low mutual coupling between elements. Mutual impedances are very important in the phasing of arrays with the corporate type of feed, and they must be made small if beam position is to be calculated accurately and simply. Corrections are possible in theory but require such complete knowledge of antenna impedance and mutual impedance for each frequency used that the practical problem was more easily solved in this case by increasing element spacing. Since the elements are more than a wavelength apart at 20 mc and are quite directive, the mutual coupling problem is small. Orientation of the array is N-S (186° true) and the beam produced is about 2° thick north to south and 30° wide east to west. Individual antennas are aimed at a 60° elevation angle so that their elevation 3-db points fall at 30° and 90° .

A gentle hillside within a quarter mile of the transmitter building was selected as the array site. This choice was dictated by the transmitter location and the available land coupled with the desire to minimize

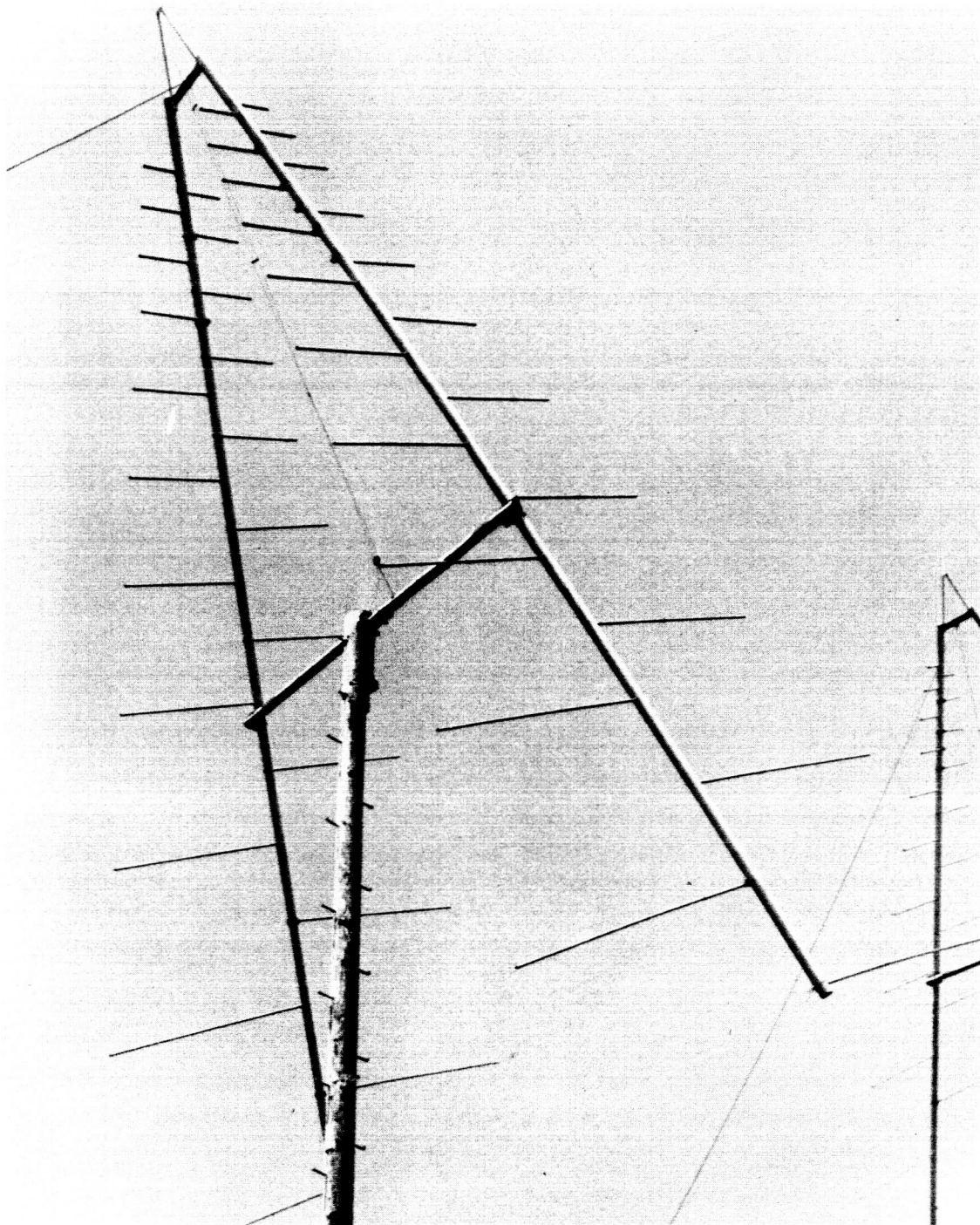


FIG. 1. SINGLE LOG PERIODIC ARRAY ELEMENT WITH THE APEX ANGLES
(α AND ψ) = 60° AND DESIGN FACTOR (τ) = 0.9.

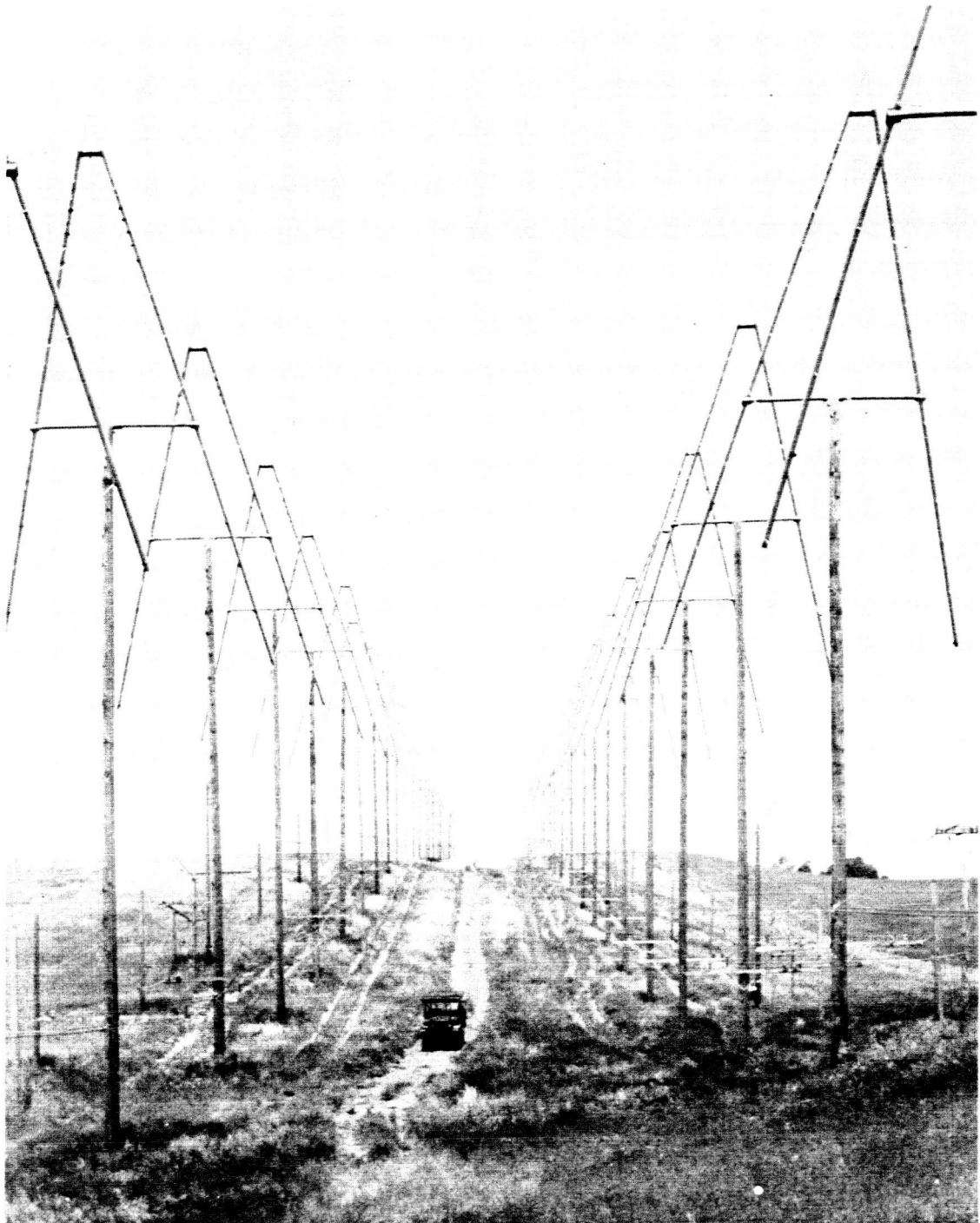


FIG. 2. ARRAY OF 48 LOG PERIOD ELEMENTS ARRANGED IN TWO 1150 FOOT ROWS OF 24 ELEMENTS.

feed line losses. The plane of the array slopes 7.5 degrees to the south. Fig. 3 compares the array's beam shape for several elevation angles with the declination of a celestial object as a function of time. It can be seen that limited steering in declination is needed to keep the 2 degree beam on target for a two-hour period. The slope of the array helps solve this problem to an extent, and a steeper slope would help even more though experience has shown that the present hill is about as steep as is practical for maintenance and phasing.

Power distribution is accomplished entirely with open wire line. Once power leaves the transmitter balanced coax, it is immediately split into a separate feed line for each row of 24 log periodics. These main feed lines are four No. 6 wires run as side-connected line to the array center approximately 1600 feet away [Refs. 3, 4]. The main tap point at the transmitter end is constructed in such a manner that the two rows of antennas can be fed with any phase relationship between 0° and 360° , thus positioning the fan beam in azimuth. Once power reaches each side of the array, it is divided three ways and split amongst the antennas as shown in Fig. 4. Each power splitting point after the three-way division is actually a movable tap bar as shown in Fig. 5 and can be positioned to give $0^\circ - 360^\circ$ phase difference between any group of antennas. This method is used between groups of 4, groups of 2, and, finally, between pairs. Since the tap bars are a half-wavelength long at 20 mc, giving $\pm 90^\circ$ phase difference, a 180° line reversal has been provided at one end of each tap bar.

All impedance matching in the array is done by means of 4-wire tapered sections and no frequency dependent lumped constants or stubs are used [Ref. 5]. Since each antenna is 470 ohms and all power tapping is done at 235 ohms, it can be seen that there are over 40 tapered sections in the array.

Phasing to any declination between $+37.5$ and -22.5 degrees can be accomplished by two men in about two hours. Phasing consists of placing the tap bars and connecting the phase reversal points to computed positions. This sets the beam to a fixed position and the correction indicated in Fig. 3 is then made with "line stretchers" which smoothly add or subtract up to 20 feet of transmission line between the groups of eight antennas.

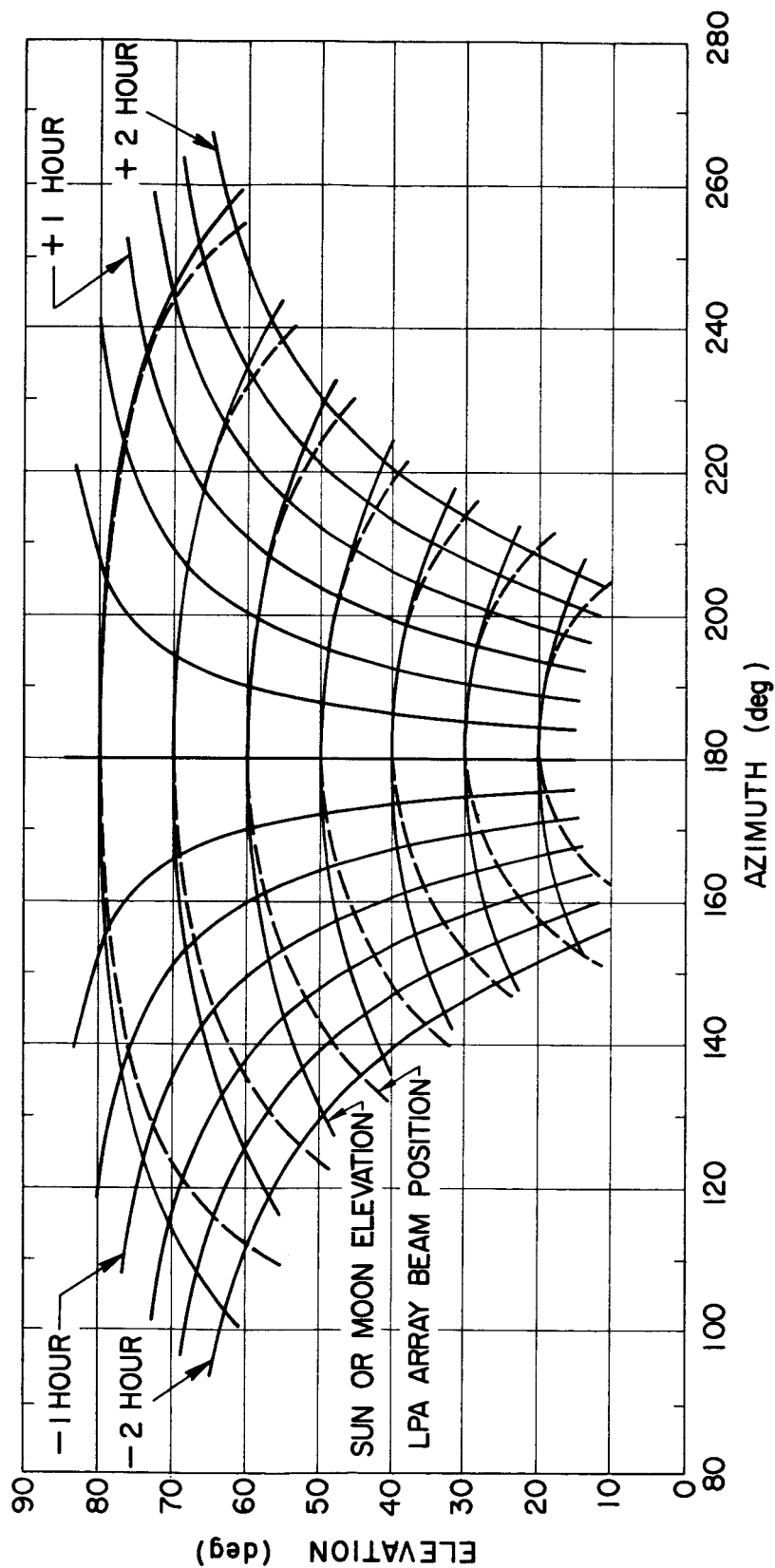


FIG. 3. TRACK OF CELESTIAL OBJECTS OF VARIOUS DECLINATIONS IN ALTITUDE AND AZIMUTH COORDINATES (solid horizontal curves) AND LOCUS OF THE ARRAY FACTOR MAXIMUM FOR A SINGLE ROW (dashed curves) AS A FUNCTION OF TIME AROUND LOWER MERIDIAN TRANSIT (solid curves labelled \pm hours).

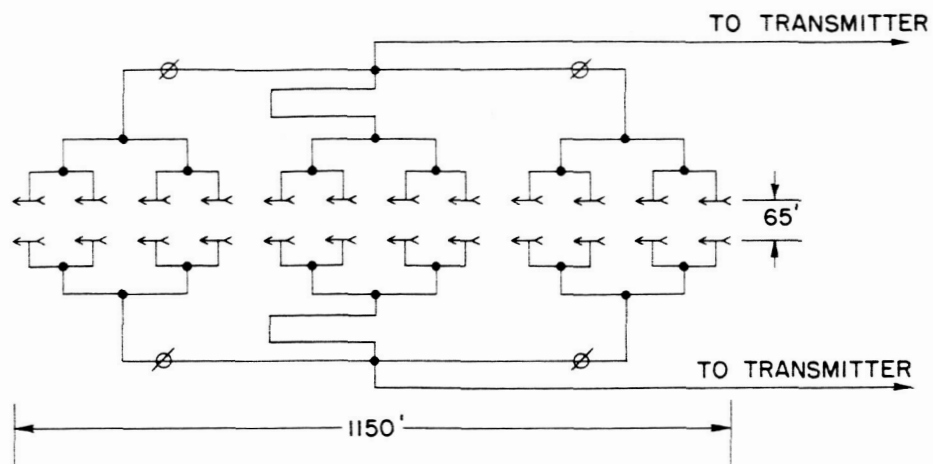


FIG. 4. SCHEMATIC OF THE ARRAY POWER DISTRIBUTION AND PHASING SYSTEM.

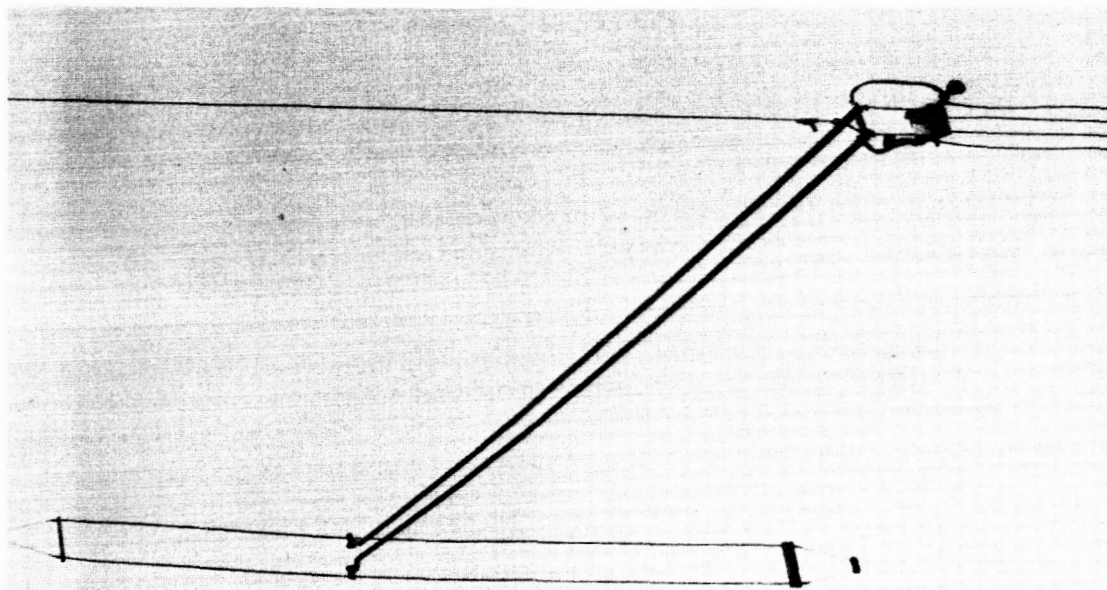


FIG. 5. SLIDING TAP BAR AT POWER SPLITTING POINT.

These stretchers are indicated by the letter Φ in Fig. 4 and are pictured in Fig. 6. They are continuously variable, telescoping tubes remotely controlled from the transmitter building, making it possible to raise or lower the antenna beam by two degrees from the central position.

An additional correction is necessary at low elevation angles where the wave must traverse a relatively long path in the ionosphere. This can be seen in Fig. 7 [Refs. 6, 7] where ionospheric refraction in degrees is plotted against vertical incidence critical frequency. Phasing to correct for refraction is normally done based on CRPL predictions for the intended operating period. The accuracy of this correction is usually sufficient though lunar work is generally restricted to elevations greater than 40° or to early morning hours when the critical frequency is low and line stretchers alone can correct the error.

Mechanical and electrical condition of the array is monitored by continuously recording cosmic noise. A typical trace is shown in Fig. 8 where the passage of the galaxy's plane at 0640 is quite evident. The large spikes on this trace are caused by local pulse transmitters which perform ionospheric sounding on an automatic program. At 10 a.m. the recording goes to zero while the transmit-receive switch is locked in the transmit position for radar warmup. The solid trace from 1200 to 1330 consists of moon echoes received in 2.5 second intervals between 2.5 second transmitted pulses. Cosmic noise records are taken using 16 kc bandwidth and the moon echoes are recorded with 1 kc bandwidth.

PERFORMANCE

Basic antenna tolerance theory [Ref. 8] is useful both in deciding on design tolerances and in evaluating performance. The directivity achievement factor is defined as

$$\zeta = \frac{\text{achieved directivity}}{\text{design directivity}} = \frac{1}{1 + \sum \epsilon_i^2}$$

where ϵ_i is the complex fractional departure from the perturbed mean of array illumination due to mechanical and electrical errors.

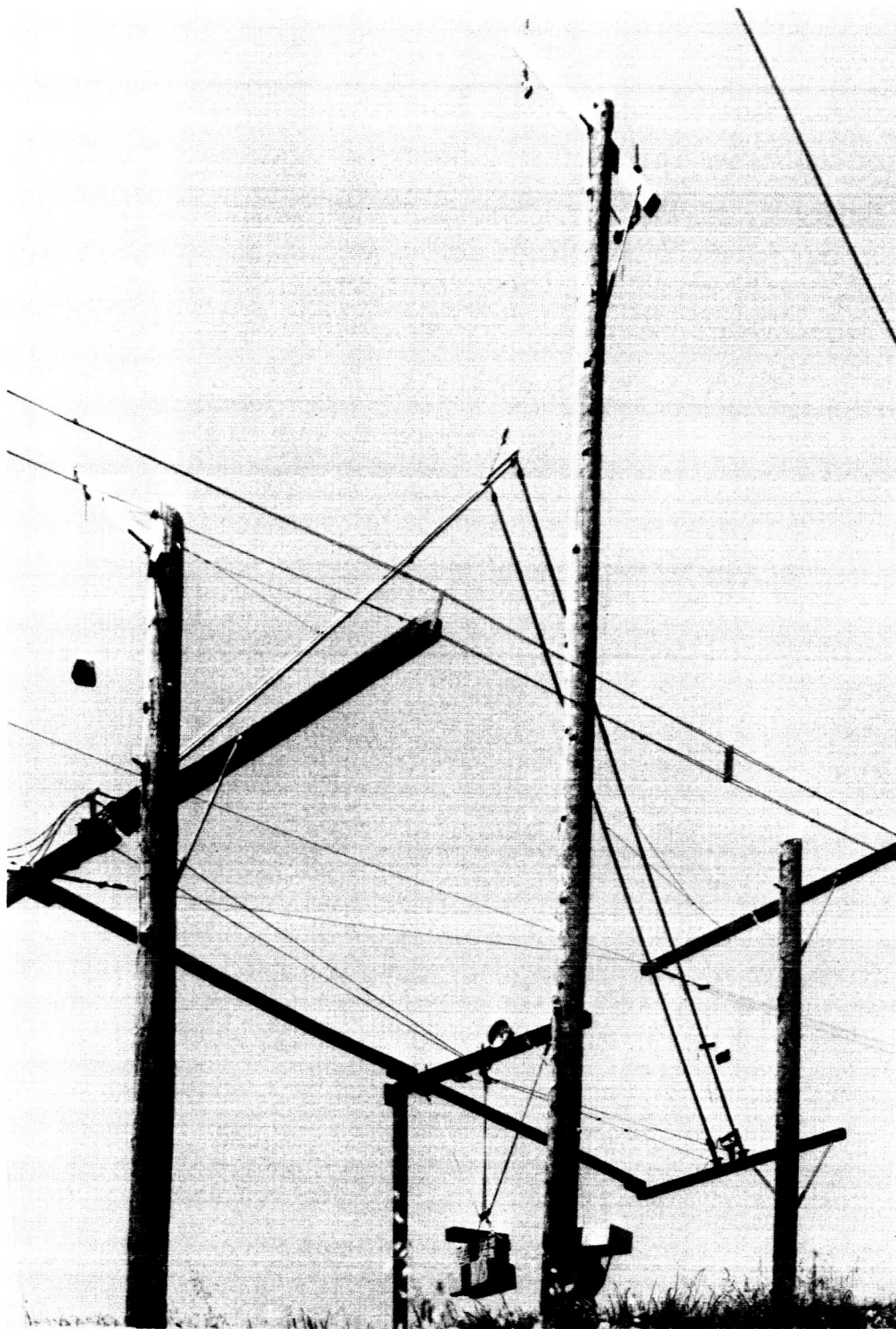


FIG. 6. MOTOR DRIVEN LINE STRETCHER SHOWN EXTENDED HALF-WAY.

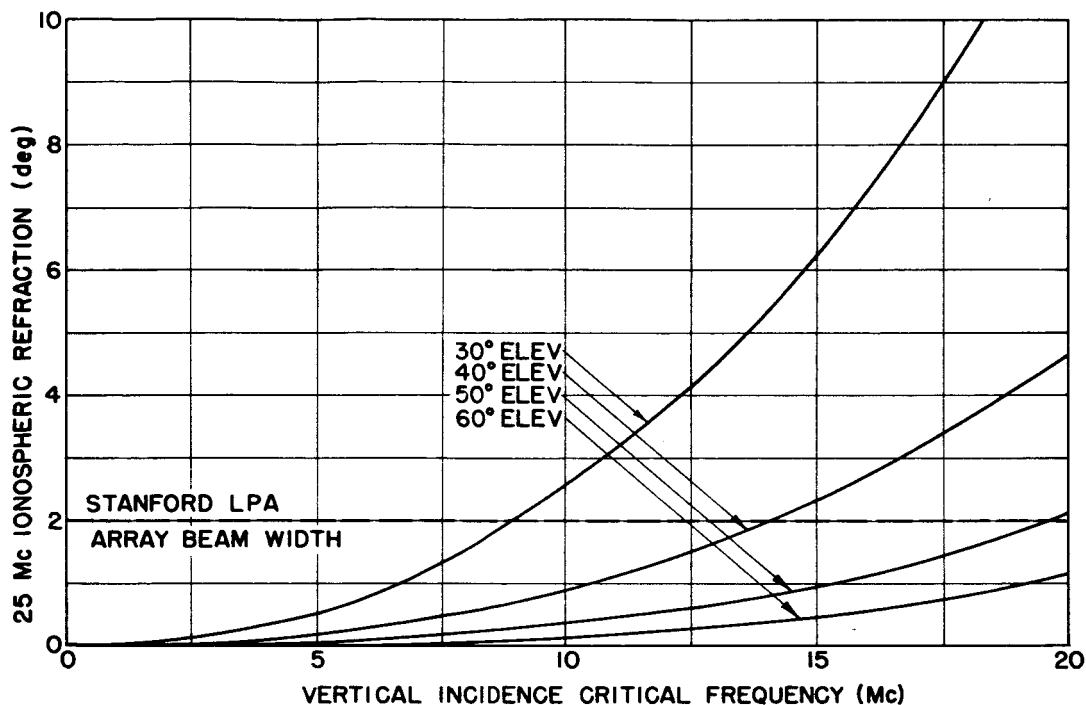


FIG. 7. IONOSPHERIC REFRACTION AT 25 Mc VS VERTICAL INCIDENCE CRITICAL FREQUENCY.

The combination of mechanical errors in antenna position (± 6 inches) and feed line lengths (± 2 inches) results in $\xi = 0.97$ which is equivalent to a loss in forward gain of 0.13 db. The main cause of directivity loss, however, lies in the relatively poor illumination caused by accepting impedance mismatches for the sake of bandwidth. In the worst measured case, this can cause a 2/1 variation in illumination or $\xi = 0.92$, which is equivalent to a loss of forward gain of 0.4 db. Illumination is usually much better than this (depending on phasing and frequency), with the ratio typically running about 1.2/1, which represents a loss of less than 0.1 db. Feed line losses amount to 0.6 db.

The array has been successfully used on several frequencies around 25 and 50 mc and has proven well able to handle the full power of both transmitters running simultaneously. Array gain has been measured at 26.3 mc using moon bounce signals compared to a reference dipole above a ground screen. Results indicate a measured gain of 25.3 db over isotropic as against 25.9 db calculated.

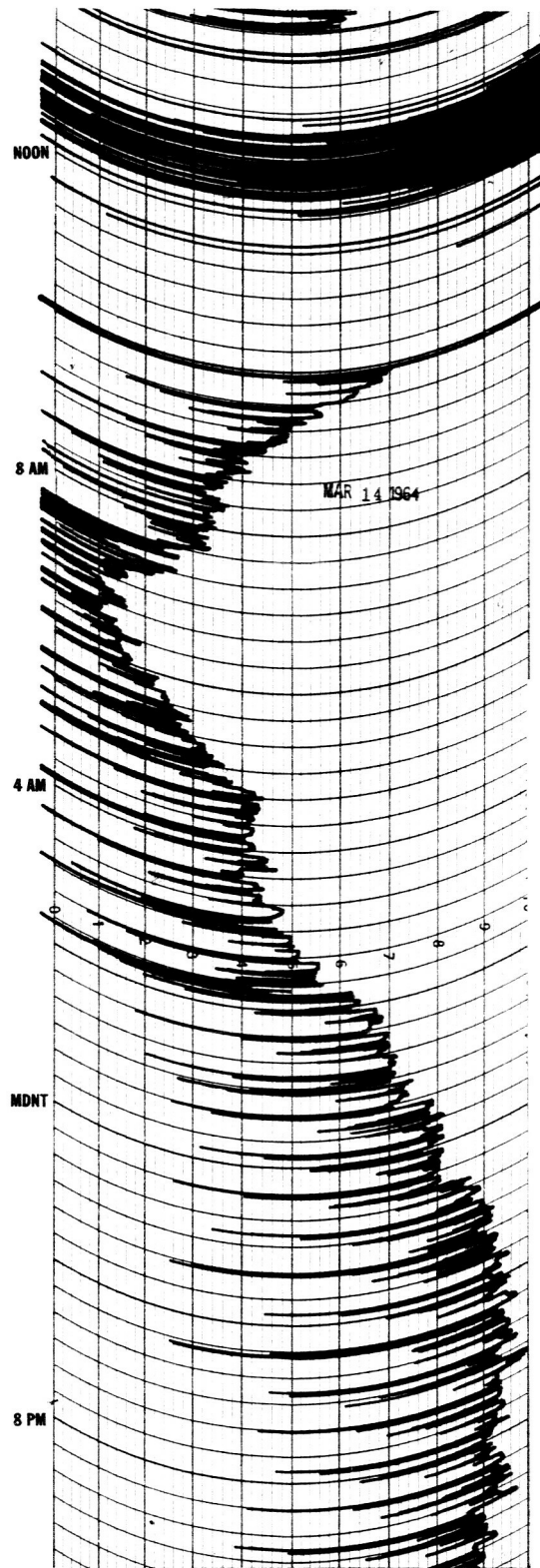


FIG. 8. TYPICAL COSMIC NOISE TRACE. Solid trace around noon PST is recording of radar echoes from the moon.

CONCLUSION

An array of this type represents a very modest investment when compared with a fully steerable antenna of equivalent aperture. The ability to employ the array on many frequencies has proven to be one of its most useful features, and the multiple element configuration makes it easily adaptable for extremely high powers. Similar power distribution and construction techniques could well be used in future installations with an individual high-power amplifier at each antenna. This would be a relatively easy and reliable method of obtaining 10 db sensitivity over the present system, and would make remote, rapid beam steering possible.

APPENDIX: DESCRIPTION OF STANFORD LPA ARRAY PHASING

The 48-element log periodic array is built on a hillside with the plane containing the array elements sloping $7\frac{1}{2}$ degrees to the south. Therefore, when the array is fed with all elements in phase, the center of its beam is directed to an elevation angle of 82.5 degrees from the southern horizon.

The power distribution of the array, a "corporate" or branching feed, is shown in Fig. 9. Directivity is achieved by summing signals from individual antennas together in such a way that waves arriving from a particular direction add in phase. This can be demonstrated for the case of a pair of radiators such as A_1 and A_2 in Fig. 10.

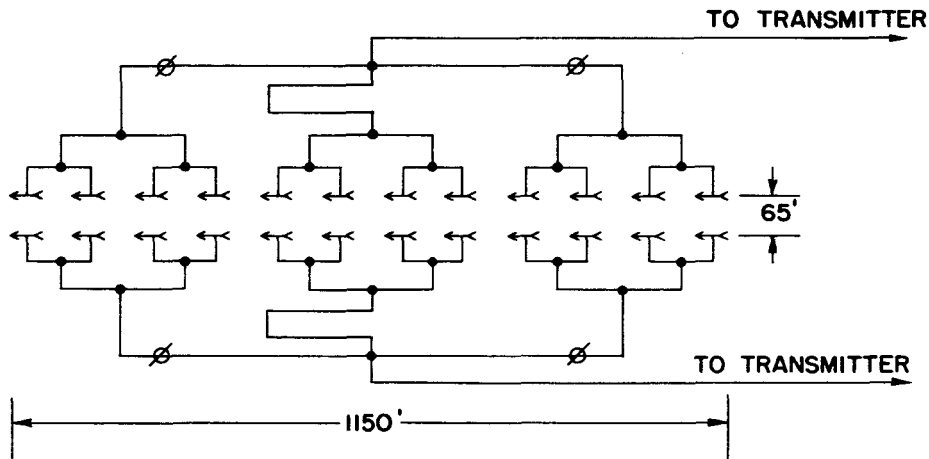


FIG. 9. SCHEMATIC OF THE ARRAY POWER DISTRIBUTION AND PHASING SYSTEM.

Energy traveling from the direction θ arrives at A_2 before A_1 . If it is desired to receive maximum energy from direction θ , it is necessary to delay the energy in A_2 by an appropriate amount before adding it to the energy from A_1 . The amount of delay required equals the time that it takes the signal to travel distance BA_1 and it can be seen that this distance is equal to $D \cos\theta$. For full steerability, then, $\cos\theta$ must be variable over all values between 0 and 1.

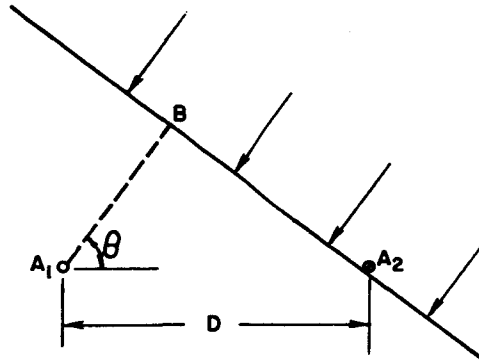


FIG. 10. TWO ANTENNAS, A_1 AND A_2 .

Figure 11 details the phasing arrangement for a single pair of antennas. If the movable tap bar is at point J, then the major lobe is directed normal to the plane containing A_1 and A_2 . Moving the tap bar toward A_1 decreases the time of energy travel from A_1 and increases it from A_2 , thus steering the array's major response away from the zenith and toward the south. In the actual array, the transmission lines between antennas and groups of antennas are labelled with the letters A through S with the letter J being at the point of zero phase difference. Examination of Figs. 9 and 10 will show that if the velocity of propagation on the transmission lines equals that of free space, then:

$$\phi = \frac{BA_1}{2}.$$

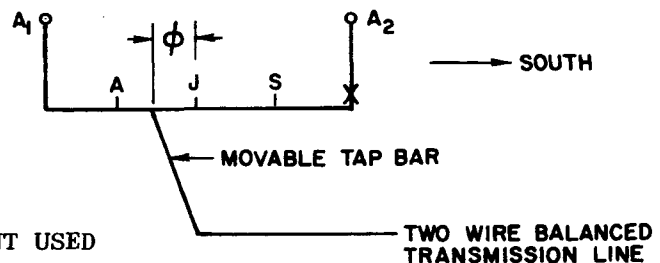


FIG. 11. PHASING ARRANGEMENT USED FOR A SINGLE PAIR OF ANTENNAS.

It is therefore necessary to move the tap bar only half of the desired delay distance. Or, stated in other words, it is necessary to be able to feed the antennas with any phase difference between 0 and 360° , and for this purpose tap bars one-half wavelength long would be necessary. To accomplish this at the lowest array frequency of 20 Mc requires tap bars about 24 feet long. Mechanical and cost considerations make the longest practicable bar about 12 feet. This means that 180° of the necessary phase difference can be achieved with tap movement. The other 180° is obtained by reversing the open wire feed line connections going to the southernmost antenna. This is indicated by the letter X in Fig. 11.

Correct phasing of groups of two antennas requires a tap bar setting that gives twice the delay required for a single pair. This can be seen by referring to Fig. 12. The tap bars are set between A_1A_2 and A_3A_4 to receive energy from elevation angle θ . Since the distance from A_2 to A_4 ($2D$) is twice the distance between A_3 and A_4 , $A_2B_2 = 2A_3B_3$. This means that when the wave front arrives at A_4 , it must travel twice as far to reach A_2 as it must to reach A_3 . The delay added by the tap therefore has to be twice as much between A_4 and A_2 as it is between A_4 and A_3 . This reasoning can be extended to show that the phase difference must again be doubled for pairs of fours.

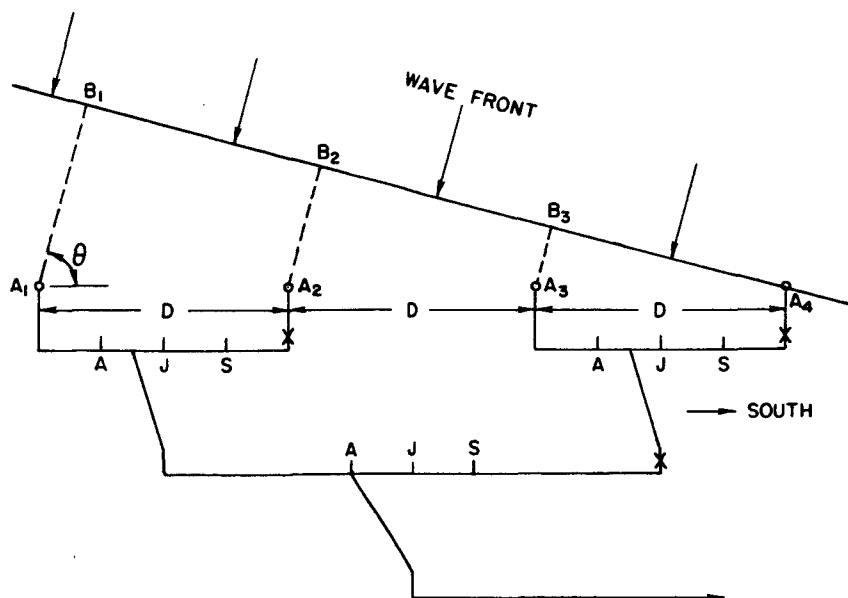


FIG. 12. PHASING ARRANGEMENT USED BETWEEN PAIRS OF ANTENNAS.

As spacing between individual antennas or groups of antennas becomes greater than 360° , additional lobes appear. Thus, whenever large phase differences are required between widely spaced antenna sections, and they cannot be achieved by moving tap points the necessary distance, it is possible to subtract an integral multiple of 360 degrees from the total. For example, if a difference of 3643° is desired, it can be obtained by subtracting 10×360 leaving 43° . This is merely saying that the central or "white" fringe of the response pattern is not always the one selected. In the case of fixed arrays operating over limited elevation angles (less than 60° in this case) with relatively narrow bandwidths, the compromise involved is negligibly small.

A typical group of tap bar settings is shown in Table I for 24.8 Mc where the letters in the left-hand column refer to tap bar position and X denotes a 180° phase reversal. The elevation angle numbers then tell the position of each usable fringe in the response pattern.

By proper setting of taps through out the array, it is thus possible to phase the beam of the groups of eight antennas to a desired elevation angle. The one problem remaining is to combine the energy from the six groups in such a manner that a narrow beam in the desired direction is achieved.

The energy from each group of eight on one row of the array is brought to a common point through equal length, balanced two-wire transmission line. One main line from the radar is connected at this point through suitable impedance transforming tapered sections. The other row of the array is connected in an identical manner to a second main transmission line which also goes to the radar. This division into two main lines makes independent operation of antenna halves possible while also allowing beam slewing or splitting in azimuth by proper adjustment of phasing lines at the radar building. Since the elevation beamwidth of eight antennas is approximately six degrees and that of the combined array is about two degrees, it is apparent that if the phasing between octets is made smoothly variable, the two degree beam could be slewed up and down by as much as three degrees. This is accomplished by the use of remotely controlled, telescoping transmission line sections (line stretchers). These are represented by the letter ϕ in Fig. 12.

As in the tap bar case, mechanical considerations limit the amount of "stretch" available to a half wavelength at 20 Mc. Thus to get the required 0 to 360° variation it is necessary to X the open wire line at each line stretcher for certain elevation angles. This limits remotely controlled slewing to about a 3° range, since the Xing is a manual operation requiring a special phasing-jeep and wrenches.

In a receiving array the necessary phase reversals could be easily accomplished with relays. The lowest power level encountered in the LPA array, however, is 6 kw and such a scheme, though possible, would be costly.

The phasing described is effective over an elevation range of 30 to 90 degrees. This limit is imposed by the 60° beamwidth of the individual log periodic elements which are directed toward an elevation of 60°. The combined beam of all elements is approximately 2° thick in elevation and 30° wide in azimuth.

TAP POSITION	ELEVATION ANGLES FOR TWIN TAPS	ELEVATION ANGLES FOR QUADRUPEL TAPS ON	ELEVATION ANGLES FOR OCTUPEL TAPS			
J	29.9 82.5	29.9 59.1 82.5	29.9	45.9	59.1	71.0 82.5
K	32.3 84.0	31.1 59.9 83.2	30.5	46.4	59.5	71.4 82.8
L	34.7 85.5	32.3 60.7 84.0	31.1	46.8	59.9	71.8 83.2
M	36.9 87.0	33.5 61.5 84.7	31.7	47.3	60.3	72.2 83.6
N	39.0 88.6	34.7 62.3 85.5	32.3	47.8	60.7	72.6 84.0
O	41.1 90.1	35.8 63.2 86.3	32.9	48.2	61.1	72.9 84.4
P	43.1	36.9 64.0 87.0	33.5	48.7	61.5	73.3 84.7
Q	45.1	38.0 64.8 87.8	34.1	49.2	61.9	73.7 85.1
R	47.0	39.0 65.6 88.6	34.7	49.6	62.3	74.1 85.5
BX	44.8	37.8 64.7 87.7	34.0	49.1	61.9	73.7 85.1
CX	46.7	38.9 65.5 88.5	34.6	49.6	62.3	74.1 85.5
DX	48.6	40.0 66.3 89.3	35.2	50.0	62.7	74.4 85.8
EX	50.4	41.0 67.1 90.0	35.7	50.5	63.1	74.8 86.2
FX	52.2	42.0 67.9	36.3	50.9	63.5	75.2 86.6
GX	54.0	43.0 68.6	36.8	51.4	63.9	75.6 87.0
HX	55.7	44.0 69.4	37.4	51.8	64.3	76.0 87.4
IX	57.4	44.9 70.2	37.9	52.3	64.7	76.4 87.8
JX	59.1	45.9 71.0	38.4	52.7	65.1	76.8 88.1
KX	60.7	46.8 71.8	39.0	53.1	65.5	77.1 88.5
LX	62.3	47.8 72.6	39.5	53.6	65.9	77.5 88.9
MX	64.0	48.7 73.3	40.0	54.0	66.3	77.9 89.3
NX	65.6	49.6 74.1	40.5	54.4	66.7	78.3 89.7
OX	67.2	50.5 74.9	41.0	54.9	67.1	78.7 90.1
PX	68.7	51.4 75.6	41.5	55.3	67.5	79.1 90.5
QX	70.3	52.3 76.4	42.1	55.7	67.9	79.4 90.8
RX	71.9	53.2 77.2	42.6	56.2	68.3	79.8
B	70.1	52.2 76.3	42.0	55.7	67.9	79.4
C	71.7	53.1 77.1	42.5	56.1	68.3	79.8
D	73.2	54.0 77.9	43.0	56.5	68.7	80.2
E	74.8	54.8 78.6	43.5	57.0	69.0	80.5
F	76.3	55.7 79.4	44.0	57.4	69.4	80.9
G	77.9	56.5 80.1	44.5	57.8	69.8	81.3
H	79.4	57.4 80.9	44.9	58.2	70.2	81.7
I	27.3 80.9	27.3 57.4 80.9	45.4	58.6	70.6	82.1
		28.6 58.2 81.7				

TABLE 1. PHASE SETTING FOR THE LOG PERIODIC ARRAY
FREQUENCY = 24.80

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